Review

A Review of Recent Advances in Research on PM$_{2.5}$ in China

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Abstract: PM$_{2.5}$ pollution has become a severe problem in China due to rapid industrialization and high energy consumption. It can cause increases in the incidence of various respiratory diseases and resident mortality rates, as well as increase in the energy consumption in heating, ventilation, and air conditioning (HVAC) systems due to the need for air purification. This paper reviews and studies the sources of indoor and outdoor PM$_{2.5}$, the impact of PM$_{2.5}$ pollution on atmospheric visibility, occupational health, and occupants' behaviors. This paper also presents current pollution status in China, the relationship between indoor and outdoor PM$_{2.5}$, and control of indoor PM$_{2.5}$, and finally presents analysis and suggestions for future research.

Keywords: PM$_{2.5}$; China; impact; I/O relationship; control

1. Introduction

In recent years, hazy weather caused by multiple pollutants, with PM$_{10}$ (cutoff sizes $\leq$ 10 μm, inhalable particles) and PM$_{2.5}$ (cutoff sizes $\leq$ 2.5 μm, particles that can enter the lungs) as the main pollutants, has affected large areas of China, lasting for a long time. It has a significant regional characteristic, which is shown in Figure 1 [1]. According to the data collected from the air quality monitoring stations in 338 big cities in China, the range of annual average concentrations of PM$_{2.5}$ in 2015 in the 388 cities was 11–125 μg·m^{-3} with an average value of 50 μg·m^{-3}. PM$_{2.5}$ was the primary pollutant for 66.8% of the severely polluted days. In 2016, the average annual concentration of PM$_{2.5}$ was 12–158 μg·m^{-3}, with an average value of 47 μg·m^{-3}, and PM$_{2.5}$ was the main pollutant for more than 80.3% of the days with severe pollution [2,3]. PM$_{2.5}$ has thus become the primary pollutant of atmospheric particulate pollution in China [4]. Compared with the coarser particles, PM$_{2.5}$ is smaller in size, larger in surface area, and more easily transported, which implies more toxicity and harmful substances that can penetrate deep into the human body. PM$_{2.5}$ can stay in the atmosphere for a long time and travel for a long distance. Therefore, it has a greater impact on human health and the quality of the atmospheric environment. It has always been a hot topic in various related research fields around the world.
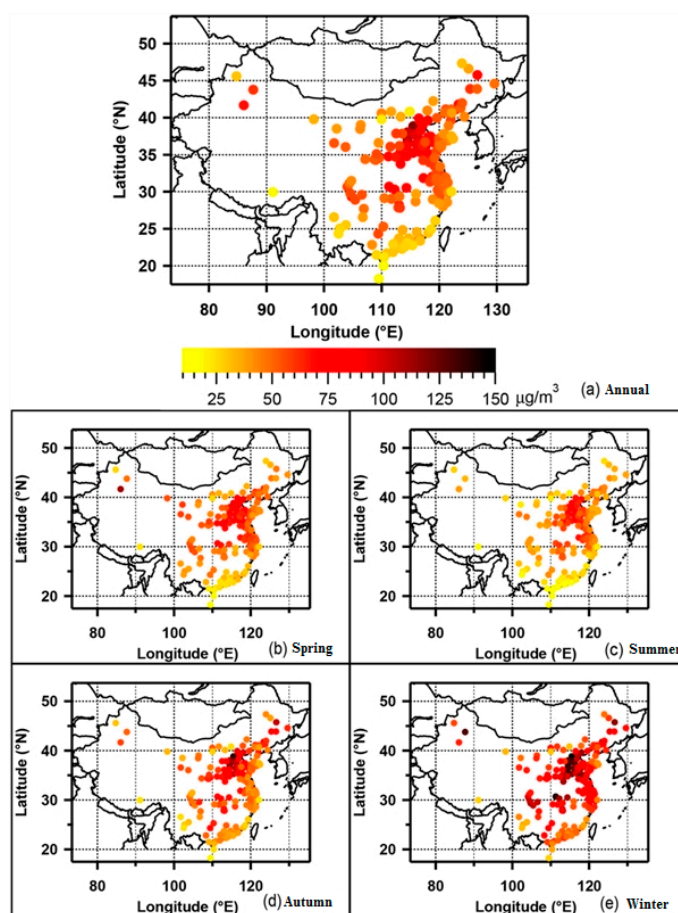
Figure 1. Spatial and temporal distribution of PM$_{2.5}$ in Chinese cities [5].

Since the 1980s, the USA and some European countries have conducted extensive studies on PM$_{2.5}$, which are mainly related to the spatial and temporal distribution of PM$_{2.5}$ concentrations, emission inventory, emission characteristics, source analysis and impact of PM$_{2.5}$ on atmospheric visibility and human health [6]. In 1997, USA took the lead in establishing environmental air quality standards for PM$_{2.5}$ and specified that the high limit of annual average PM$_{2.5}$ concentration is 15 μg·m^{-3}, and the 24 h concentration limit is 65 μg·m^{-3}.

Two revisions have been made since then. Other countries (organizations) have also set PM$_{2.5}$ concentration limits of their own (see Table 1). In China, it was not until in 2012 when the current ambient air quality standard was established and the concentration limit of PM$_{2.5}$ was incorporated into the standard. The standard adopts the maximum limits set by the World Health Organization (WHO), i.e., the annual average concentration limit is 15 μg·m^{-3}, and the 24-h concentration limit is 35 μg·m^{-3}. However, it was not enforced nationwide until 2016. According to the latest PM$_{2.5}$ concentration data published by WHO on 17 April 2016, the annual average PM$_{2.5}$ concentration among 210 cities in China was in the range of 11–128 μg·m^{-3} [7]. It is noted that only 1.4% of the cities were able to meet the first level standard in China. The histogram distribution of PM$_{2.5}$ concentrations is shown in Figure 2 [7]. It can be concluded that the problem of PM$_{2.5}$ pollution in China is very serious and it is urgent to take action to control PM$_{2.5}$ emission without delay.

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Table 1. Implementation time table for each country/organization on PM$_{2.5}$ concentration limit.

Country/Organization	Annual Average Limit ($\mu g \cdot m^{-3}$)	Daily Average Limit ($\mu g \cdot m^{-3}$)	Notes	Web References
USA-1	15	65	Established in 1997	
USA-2	15	35	Established in 2006	[8]
USA-3	15	12	Established in 2012	
Australia	8	25	Established in 2003, not enforced till now	[9]
WHO air quality goal (AQG)	10	25	Published in 2005, and the limit is mainly for developing countries	
WHO transition target-1 (the most flexible limit)	35	75	Compared with AQG value, long-term exposure at these levels increases the risk of death by about 15%	[10]
WHO transition target-2	25	50	Among other health benefits, exposures at this level reduce the risk of death by about 6% (2% to 11%) compared with transition target-1	
WHO transition target-3	15	37.5	This is the lowest level for long-term exposure to PM$_{2.5}$, at which total mortality, cardiopulmonary disease mortality and lung cancer mortality will increase with over 95% confidence	
EU-1 (2010–2015)		25	Published in 2008, executed in 2010, and not allowed to go beyond the limit in 2015	[11]
EU-2 (2015–2020)		20	Not enforced until 2020	
Singapore (long term target)	10	25	Established in 2008	
Singapore-1 (2008–2014)	15		Established in 2008	[12]
Singapore-2 (2015–2020)	12	37.5	Established in 2015	
Japan	15	35	Established in 2009	[13]
India	40	60	Established in 2009	[14]
China level 1	15	35	Established in 2012, fully implemented in 2016	[15]
China level 2	35	75		

EU: European Union.

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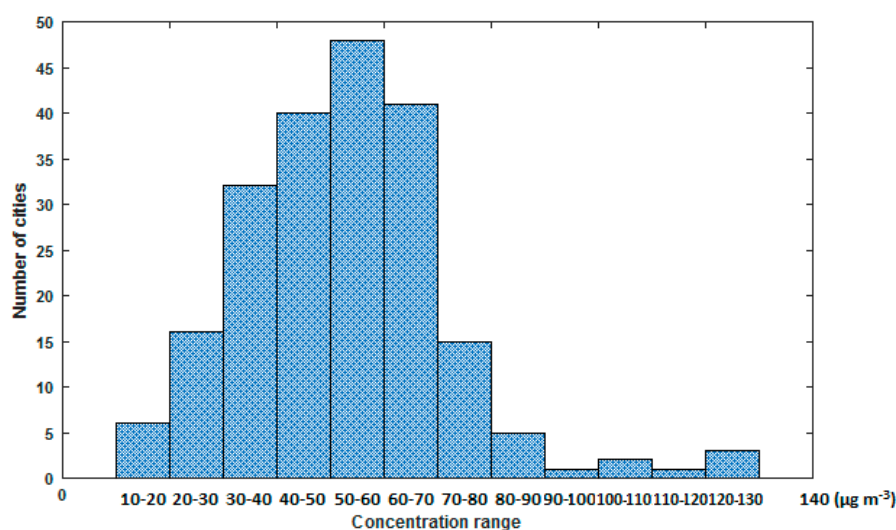
Figure 2. Histogram distribution of PM$_{2.5}$ concentration [7].

Due to the lack of long-term and large-scale monitoring data, compared with developed countries, research on PM$_{2.5}$ in China started late and can be divided into three stages. The first stage was before 2004, and at the time the research on PM$_{2.5}$ was of small scale and tentative. The studies were conducted mainly in major cities such as Beijing, Guangzhou, Nanjing and Shanghai. There were few studies on small and medium-sized cities, but only simple statistical and principle analysis on the data had been carried out [8–14]. For example, Wu et al. [16] conducted two-year data monitoring on PM$_{2.5}$ concentration in Guangzhou, Wuhan, Lanzhou and Chongqing, and found that the PM$_{2.5}$ concentration in the atmosphere generally exceeded 2–8 times of the limit set by the U.S. standard. Wang et al. [17] collected and analyzed nearly 10-year PM$_{2.5}$ concentration data in urban and clean areas in China, and concluded that PM$_{2.5}$ pollution is heavy in most parts of China. At the same time, He et al. [18] also collected PM$_{2.5}$ concentration data from July 1997 to September 2000 in the city center and urban area in Beijing. It was shown that the seasonal variation of PM$_{2.5}$ concentration was remarkable, with the highest in winter and the lowest in summer. Yang et al. [19] set up PM$_{2.5}$ sampling points in Chegongzhuang and Tsinghua University in Beijing and started to discuss on the chemical composition characteristics of PM$_{2.5}$. Huang et al. [20] collected 50 samples in five typical urban function areas of Nanjing in winter, spring and autumn and analyzed the PM$_{2.5}$ pollution level. Wang et al. [21] studied the PM$_{2.5}$ concentration in spring in Nanjing. Yang et al. [22] started to consider the source of PM$_{2.5}$ in the atmosphere in Beijing.

The second stage is from 2004 to 2011. Although the research areas on PM$_{2.5}$ gradually expanded, overall the research was still relatively straightforward, which were mainly related to the toxic effects of PM$_{2.5}$ on cells [23–28], source analysis [29–34], and chemical composition analysis [35–42], etc. The third stage is from 2012 till now, due to the establishment of China's PM$_{2.5}$ air quality standards and gradual developments of nationwide PM$_{2.5}$ observation stations, the number of researches on PM$_{2.5}$ have increased exponentially. Since then, more and more disciplines have become involved in the study on PM$_{2.5}$, but overall the research still lags behind, compared with developed countries. This paper aims at studying the advances in PM$_{2.5}$ on research in China in recent years from the following four aspects: the sources of PM$_{2.5}$, the influence of PM$_{2.5}$, the correlation of indoor and outdoor PM$_{2.5}$ concentration and the control of PM$_{2.5}$, and trying to explore new insights for the scholars of future research.

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2. Sources of PM$_{2.5}$

2.1. Sources of PM$_{2.5}$ in Urban Atmosphere

The sources of PM$_{2.5}$ in urban atmosphere are very complicated. They can mainly be categorized into primary and secondary sources, of which primary sources refer to the direct emissions of various sources such as combustion sources. The secondary sources come from particles generated from the chemical processes in the atmosphere that oxidize the original gaseous components, such as sulfates and so on [43]. Currently, there are three methods, which are mostly often used to analyze the sources of atmospheric particulate matters, which are source inventory method, source model (dispersion model) method and receptor model method. The receptor model method is the most commonly used method for source analysis of PM$_{2.5}$ in China [44]. The receptor model includes chemical mass balance method (CMB), positive matrix factorization (PMF) method, factor analysis (FA) method, principal component analysis (PCA) method, multi-linear engine (ME2) method and UNMIX method (UNMIX is a principal component method, but is based on geometrical analysis of the measurement dataset) [45]. Table 2 summarized the researches that have been conducted by the Chinese scholars on PM$_{2.5}$ sources analysis. Some scholars also integrated these basic models with other methods for PM$_{2.5}$ source apportionment analysis. For example, Wang et al. [46] used PMF model to derive PM$_{2.5}$ contribution sources, and then used backward trajectory model to identify four potential directions to identify PM$_{2.5}$ contribution sources, which shows that there was a clear difference in the distribution rates among all the different sources at different directions.

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Table 2. Modeling methods and analysis on sources of PM$_{2.5}$.

Method	Reference	Location	Sampling Time Period	Main Sources of PM$_{2.5}$ and Their Contribution Rates
CMB	[34]	Ningbo	15–24 March 2010; 31 May–9 June 2010; 10–19 December 2010	Urban dust (20.42%), coal dust (14.37%) and vehicle exhaust (15.15%)
	[47]	Urumchi	19–30 January 2013	Urban dust (24.7%), coal dust (15.6%) and secondary particles (38.0%)
	[48]	Qizhou	September 2013; February–March 2014; May 2014	Dust (21–35%), secondary particles (25–26%) and vehicle exhaust (21–26%)
	[49]	Ningbo	25–31 January 2010; 31 May–6 June 2010; 10–16 October 2010	Urban dust (19.9%), coal dust (14.4%), secondary sulfate (16.9%), vehicle exhaust (15.2%), secondary nitrate (9.78%) and secondary organic carbon (8.85%)
	[50]	Tianjin	13–20 May 2010; 20–27 October 2010; 19–26 December 2010	Open source (urban dust, soil dust and construction cement dust, total contribution of 30%),Secondary particles (secondary sulfate, secondary nitrate and secondary carbon, total contribution of 28%), coal dust (19.6%) and vehicle exhaust (15.9%)
	[51]	Chongqing	6–28 February 2012; 6–28 August 2012; 19–27 October 2012; 7–29 December 2012	Secondary particles (30.1%) and moving source (27.9%)
	[52]	Beijing	August 2012–July 2013, continuous for 5 to 7 days per month	Secondary inorganic salts (36%), organic matter (20%), vehicle/fuel (16%), coal burning (15%), soil dust (6%) and others (7%)
	[53]	Xining	26 February–4 March 2014; 22–28 April 2014; 19–25 September 2014	Urban dust (26.24%), coal dust (14.5%), vehicle exhaust (12.8%), secondary sulphate (9.0%), biomass burning (6.6%), secondary nitrates (5.7%), steel dust (4.7%), construction dust (4.4%), soil dust (4.4%), food and beverage emissions (2.9%) and other unidentified sources (5.2%)
	[54]	Xingtai	24 February–15 March 2014; 22 April–19 May 2014; 15–28 July 2014	Coal dust (25%), secondary inorganic particles (sulfate and nitrate, 45%), vehicle exhaust (11%), dust (9%), soil dust (3%), construction and metallurgical dust (1%) and other unidentified sources (3%)

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Table 2. *Cont.*

Method	Reference	Location	Sampling Time Period	Main Sources of PM$_{2.5}$ and Their Contribution Rates
PMF	[55]	Wuhan	July 2011–February 2012	Vehicle sources (27.1%), secondary sulphates and nitrates (26.8%), manufacturing emissions (26.4%) and biomass combustion (19.6%)
	[56]	Chengdu	29 April–17 May 2009; 6 July–6 August 2009; 26 October–26 November 2009; 1–31 January 2010	Soil dust and raise dust (14.3%), biomass combustion (28.0%), vehicle sources (24.0%) and secondary nitrates/sulfates (31.3%)
	[46]	Shenzhen	January–December 2009	Secondary sulphate (30.0%), vehicle sources (26.9%), biomass combustion (9.8%) and secondary nitrates (9.3%)
	[57]	suburbs of Shanghai	23 December 2012–18 February 2014	Secondary aerosol (50.8%), fuel combustion (17.5%), biomass combustion/sea salt (17.2%), raise dust/construction dust (7.7%), and coal-burning/smelting dust (6.9%)
	[58]	North China	3 January–11 February 2014	Coal combustion (29.6%), biomass combustion (19.3%) and vehicle sources (15.9%)
	[59]	Lanzhou	Winter 2012 and summer 2013	Steel industry, secondary aerosols, coal combustion, power plants, vehicle emissions, crustal dust, and smelting industry contributed 7.1%, 33.0%, 28.7%, 3.12%, 8.8%, 13.3%, and 6.0%, respectively, in winter, and 6.7%, 14.8%, 3.1%, 3.4%, 25.2%, 11.6% and 35.2% in summer
	[60]	Chongqing	2012–2013	Secondary inorganic aerosols (37.5%), coal combustion (22.0%), other industrial pollution (17.5%), soil dust (11.0%), vehicular emission (9.8%) and metallurgical industry (2.2%)
	[61]	Yellow River Delta National Nature Reserve (YRDNNR)	January–November 2011	Secondary sulphate and nitrate (54.3%), biomass burning (15.8%), industry (10.7%), crustal matter (8.3%), vehicles (5.2%) and copper smelting (4.9%)
	[62]	Shanghai	October 2011–August 2012	Coal burning (30.5%), gasoline engine emission (29.0%), diesel engine emission (17.5%), air-surface exchange (11.9%) and biomass burning (11.1%)
	[63]	Zhengzhou	April 2011–December 2013	Coal burning (29%), vehicle (26%), dust (21%), secondary aerosols (17%) and biomass burning (4%)
	[64]	Qingshan District, Wuhan	15 November–28 December 2013	Traffic exhaust (28.60%), industry (27.10%), road dust (22%), coal combustion (13.20%) and building dust (9.5%)

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Table 2. *Cont.*

| Method	Reference	Location	Sampling Time Period	Main Sources of PM$_{2.5}$ and Their Contribution Rates
FA	[65]	Beijing	16 January–28 February 2013	Industrial dust and human activities (40.3%), biomass combustion and building dust (27.0%), soil and wind induced dust (9.1%), fossil fuel sources (4.9%), electronic waste sources (4.8%) and regional migration sources (4.6%)
PCA	[66]	Hangdan	January, April, July and October 2015	Secondary aerosol source, transportation, fossil fuel and biomass burning (46.5%), soil and construction dust (19.5%), steel industry (19.5%) and transportation (9%)
	[67]	Hangdan	October 2012–January 2013	Industry and coal burning (33.3%), secondary aerosol and biomass burning (21.7%), vehicle (12.8%) and road dust (9.1%),
WRF/Chem+ observation data analysis	[68]	Guangzhou	January–December 2013	Moving sources (37.4%), industrial emissions (32.2%), electricity emissions (12.2%), residential emissions (6.6%) and others (11.6%)
PMF and backward trajectory model	[69]	Heze	13–22 August 2015; 21–30 October 2015; 14–23 January 2016 7–16 April 2016	Secondary inorganic salt (32.61%), vehicle emissions (22.60%), raise dust (19.64%), coal dust (16.25%) and construction cement dust (9.00%)
Chemical mass balance gas constraint-Iteration (CMBGC-Iteration)	[70]	Tianjin	April 2014–January 2015	Secondary sources (30%), crustal dust (25%), vehicle exhaust (16%), coal combustion (13%), SOC (7.6%) and cement dust (0.40%)
Ensemble-average of CMB, CMB-Iteration, CMB-GC, PMF, WALSPMF, and NCAPCA				Secondary sources (28%), crustal dust (20%), coal combustion (18%), vehicle exhaust (17%), SOC (11%) and cement dust (1.3%)
Community Multiscale Air Quality (CMAQ) model	[71]	25 Chinese provincial capitals and municipalities	2013	Power plants (8.7–12.7%), agriculture NH3 (9.5–12%), windblown dust (6.1–12.5%) and secondary organic aerosol (SOA) (5.4–15.5%)
Particle Induced X-ray Emission(PIXE), XRay Fluorescence (XRF), and PMF	[72]	Xigngzhen District, Beijing	19 May 2007–19 July 2013	Coal burning (29.2%), vehicle exhaust and waste incineration (26.2%), construction industry (23.3%), soil (15.4%) and industry with chlorine (5.9%)
Inventory-Chemical Mass Balance (I-CMB)	[73]	Beijing	2012	Coal (28.06%), vehicle (19.73%), dust (17.88%), industry (16.50%), food (3.43%) and plant (3.40%)

CMB: chemical mass balance method; PMF: positive matrix factorization; FA: factor analysis; PCA: principal component analysis; WRF: Weather Research and Forecasting; WALSPMF: Weighted Alternating Least Squares Positive Matrix Factorization; NCAPCA: Non-negative Constrained Absolutely Principle Analysis.

Shi et al. [70] employed a chemical mass balance gas constraint-Iteration (CMBGC-Iteration) method for source appointment analysis in Tianjin. The outcomes from this method were compared with the ensemble-average outcomes of CMB, CMB-Iteration, CMB-GC, PMF, WALSPMF (Weighted Alternating Least Squares Positive Matrix Factorization), and NCAPCA (Non-negative Constrained Absolutely Principle Analysis), and it was found that they were comparable. From Table 2, it can be found that the sampling time of most scholars is periodical, although sometimes with very long time span, the sampling work was done only in typical months of each season, or even a few days in a typical month. Although there are contingency and uncertainty with the measurements, it can still reflect the contribution source categories of $PM_{2.5}$ to some extent. Meanwhile, it is observed that the contribution rates of different sources to $PM_{2.5}$ from different scholars vary greatly, and there are obvious differences, even for the same city. It could due to the differences in the sampling time of the study, contribution categories, regions, climate, energy structure, atmospheric environment, etc.

2.2. Sources of Indoor $PM_{2.5}$

Sources of indoor $PM_{2.5}$ can be divided into outdoor sources and indoor sources (see Figure 3). There is a time lag for the impact of outdoor $PM_{2.5}$ concentration on the indoor $PM_{2.5}$ to take effect. The indoor pollution sources are usually generated transiently and intermittently, resulting in large fluctuations in the concentration of indoor particulates [74].
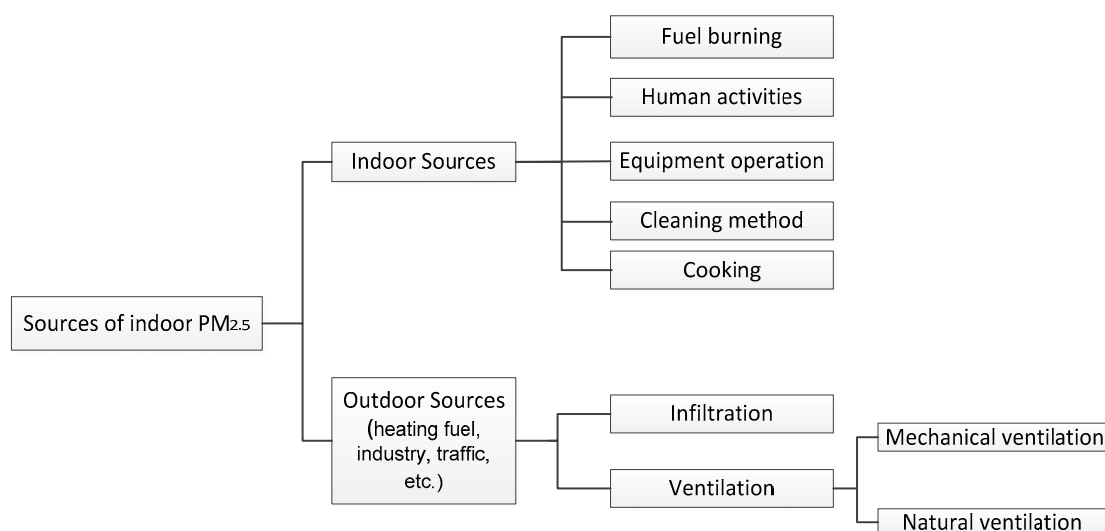
Figure 3. Sources of indoor $PM_{2.5}$.

2.2.1. Outdoor Sources

The outdoor sources come from heating fuel, industry, traffic, etc. [34,46–73], due to the rapid industrialization, high energy consumption and large proportion of coal (60–70%) in the structure of energy sources in China. It has been acknowledged that there is close correlation between indoor and outdoor $PM_{2.5}$ concentration levels, and outdoor $PM_{2.5}$ is the main source of indoor $PM_{2.5}$ pollution [75–77]. Wang et al. [78] showed that there was a significant correlation between indoor and outdoor concentrations of $PM_{2.5}$ for rooms with normal airtightness and no air conditioning filter system. The indoor/outdoor (I/O) $PM_{2.5}$ concentration ratio was up to 0.867. The correlation will be more obvious when the outdoor pollution level increases. Ji and Zhao [79] presented that 54–63% of indoor $PM_{2.5}$ came from outdoors when the windows were closed, and it increased to as high as 92% when the windows were open. Han et al. [75] concluded that indoor $PM_{2.5}$ concentration is significantly correlated with outdoor $PM_{2.5}$ concentration but with 1 to 2 h delay, and the differences in

the time lag effect are due to differences in environmental meteorological conditions such as outdoor air temperature, humidity ratio and wind direction.

2.2.2. Indoor Sources

There are many different types of indoor $PM_{2.5}$ sources, which mainly come from fuel combustion, human activities, equipment operation, cleaning, and cooking. Indoor combustion of fuels such as coal, natural gas, alcohol, and mosquito coils can lead to the rapid increase of indoor $PM_{2.5}$ concentration. Zhang and Duan [80] showed that burning a mosquito coil ring could release 626 $\mu g \cdot m^{-3}$ of $PM_{2.5}$, which is 8.3 times the concentration limit allowed for the residential environment. Li et al. [81] concluded that $PM_{2.5}$ concentration in households using coal to cook was significantly higher than those using gas or electricity, and if coal is switched to gas or electricity, the $PM_{2.5}$ concentration in the kitchen could be reduced by 40–70%. Zhou et al. [82] indicated that human activities such as walking, dressing and cleaning could result in increased indoor $PM_{2.5}$ concentration by 33%. Gui et al. [83] conducted experiments on dry-sweeping, wet-sweeping and air-dry sweeping in an office. The average indoor $PM_{2.5}$ concentrations before cleaning were 47.3 $\mu g \cdot m^{-3}$, 40.6 $\mu g \cdot m^{-3}$ and 39.4 $\mu g \cdot m^{-3}$, respectively. The average indoor $PM_{2.5}$ concentrations were 109.7 $\mu g \cdot m^{-3}$, 97.5 $\mu g \cdot m^{-3}$ and 43.3 $\mu g \cdot m^{-3}$ after cleaning. The average $PM_{2.5}$ concentrations were increased by 2.3 times, 2.3 times and 1.1 times, respectively. Therefore, it is recommended to use wet sweeping under ventilated condition as much as possible. Sun et al. [84] found that the printer also plays a role in contributing to indoor $PM_{2.5}$ concentration, and that $PM_{2.5}$ released by printers with different performances was quite different. Zhang et al. [85] advised that different cooking habits, cooking methods, raw materials and even seasoning strongly influence the composition of particulate matters.

2.3. PM_{2.5} Reginal Variations

$PM_{2.5}$ pollution has significant regional characteristics. The pollution conditions within or between regions is interrelated. $PM_{2.5}$ pollution in one region is affected not only by local pollution sources but also outside regions to different levels of extent. A large number of studies have shown that $PM_{2.5}$ pollution has regional transmission characteristics [86–90]. For example, the study from Xue et al. [86] showed that about 22%, 37%, 28%, and 14% of the annual average $PM_{2.5}$ concentration in Jin-Jin-Ji, the Yangtze River Delta, Pearl River Delta and Chengdu-Chongqing city group were contributed by outside region, respectively. The contribution of $PM_{2.5}$ concentration from outside region for Hainan, Shanghai, Jiangsu, Zhejiang, Jilin and Jiangxi were all higher than 45%. For Beijing, Tianjin and Shijiazhuang, the outside contributions accounted for 37%, 42% and 33%, respectively. At the same time, some scholars also found that the degree of $PM_{2.5}$ pollution in the same region gradually weakened from the urban center to the suburbs [91–94]. Zhang et al. [92] analyzed $PM_{2.5}$ concentration data from 13 monitoring sites in Xi'an from 1 January to 26 April 2013, and found that the $PM_{2.5}$ concentration in this area decreased from west to east, which is consistent with the characteristics of altitude and wind direction. Analysis from Zhao et al. [93] on the characteristics of $PM_{2.5}$ and PM_{10} pollution in Beijing showed that the concentrations of PM gradually increased from the northern mountain region to the southern plain areas. In the central urban area, the concentrations were higher in the western part than those in the eastern part. There were some differences on the $PM_{2.5}$ concentration levels between urban and rural areas in some cases. Wang et al. [95] indicated that although there were differences in the degree of $PM_{2.5}$ pollution between the urban and suburbs areas, their variation trends were basically the same, which means that the degree of pollution in the suburbs area was affected to some extent by the high $PM_{2.5}$ concentration in the city center.

2.4. Impact of Meteological Factors on PM_{2.5} Variations

Meteorological factors can significantly affect $PM_{2.5}$ mass concentration, which can help to reduce or aggravate the urban air pollution. Song et al. [96] found that during high temperature weather in summer, although $PM_{2.5}$ mass concentration was 2 to 3 times higher than that of low temperature

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period, the high temperature weather was still helpful to the diffusion of pollutants. Zheng et al. [97] also indicated that the effect of rainfall on the removal of particulate matter was obvious. The average $PM_{2.5}$ concentration decreased by 56.3% following the rainfall, and $PM_{2.5}$ mass concentration was less than 60 $\mu g \cdot m^{-3}$ within 72 h after the rainfall. Within 1 h after the rainfall, the $PM_{2.5}$ concentration level stayed almost unchanged, and it kept declining within the next 12 h. Jiang and Li [98] showed that there was a negative correlation between $PM_{2.5}$ mass concentration and precipitation. Large mixed layer thickness and unstable atmospheric layer junction help to the reduction of $PM_{2.5}$ mass concentration. In Nanjing, the $PM_{2.5}$ mass concentration was relatively low under northeast and southwest wind conditions, and it also had a negative correlation with the wind speed. High humidity did not help with the reduction of $PM_{2.5}$ mass concentration but would affect the visibility. Humidity ratio of 60–70% is a turning zone for $PM_{2.5}$ pollution. Some other scholars also showed that wind speed, wind direction, atmospheric stability, air humidity, rainfall, etc. also have significant impacts on the diffusion, dilution, agglomeration and retention of $PM_{2.5}$ [99–102]. In addition, the meteorological factors that are mainly related to $PM_{2.5}$ concentrations in different cities also vary due to the differences in emission intensity and diffusion conditions of pollutants. Zhang et al. [103] found that the meteorological factors related to $PM_{2.5}$ concentration during winter in Shijiazhuang were relative humidity and average wind speed; the main meteorological factors related to $PM_{2.5}$ concentration in Xi'an were relative humidity, average wind speed and maximum sustained wind speed; the ones in Beijing are relative humidity, average daily temperature, average wind speed, maximum sustained wind speed and minimum temperature; the ones in Taiyuan were daily average temperature, relative humidity, average wind speed, maximum and minimum temperature, and maximum sustained wind speed; and the ones in Guangzhou were relative humidity, average wind speed, maximum temperature and rainfall.

3. Various Impacts of $PM_{2.5}$ Pollution

3.1. Impacts on Atmospheric Visibility

Visibility refers to the maximum distance that a person with normal eyesight can see clearly the contour of the target under the prevailing weather conditions, and it is an indicator on the transparency of the atmosphere. Some scholars pointed out that in recent years the atmospheric visibility in China has reduced sharply, which is closely related to the increase of the concentration of fine particulate matter ($PM_{2.5}$) in the atmosphere [104,105]. Low-visibility weather has a significant impact on traffic, health, ecological landscape, etc. Visibility is also the most direct indicator of a city's air quality [106]. At present, the study on the relationship between $PM_{2.5}$ and atmospheric visibility mainly focuses on the statistical relationship among atmospheric visibility, $PM_{2.5}$ concentration and meteorological factors. The results show that there is an obviously negative correlation between atmospheric visibility and $PM_{2.5}$ mass concentration [107]. Some meteorological parameters such as relative humidity [106,108,109] also affect the relationship between $PM_{2.5}$ and atmospheric visibility. For example, Hao et al. [108] pointed out that when the relative humidity was ≤19%, there was an obvious logarithmic relationship between $PM_{2.5}$ mass concentration and atmospheric visibility; when the relative humidity was 20–29%, the relationship became exponential; and when the relative humidity was ≥30%, power relationship became obvious. However, Wang et al. [110] presented different viewpoints. They suggested that $PM_{2.5}$ mass concentration is not related to atmospheric visibility. The reason why $PM_{2.5}$ can affect the visibility is due to the difference in the chemical composition of $PM_{2.5}$ in different seasons as well as difference in meteorological conditions.

3.2. Impacts on Regional Climate

The energy balance of the Earth-atmosphere system determines the state of the climate. In general, the energy balance of the Earth-atmosphere system is in dynamic equilibrium. However, if the balance is disturbed or destroyed, it causes the Earth climate to change [111]. There are direct and indirect impacts of $PM_{2.5}$ on the climate. For the direct impact, the $PM_{2.5}$ affects the earth-atmosphere radiation

budget by scattering and absorption of solar radiation and ground longwave radiation. At the same time, $PM_{2.5}$ can block the solar beams from reaching the Earth's surface, and increase the optical density of the visible light, thus cutting down the solar energy that reaches the Earth's surface. As a result, the ground temperature goes down and the temperature at high altitude rises. Zhang et al. [112] found that the aerosol optical depth (AOD) at 500 nm in North China reaches 0.60–1.00 during the pollution period, where the fine-mode particles contribute more than 90% to the aerosol extinction characteristics and the single-scattering albedo of the aerosol is lower than 0.88. Hu and Liu [113] pointed out that there is a negative correlation between $PM_{2.5}$ concentration and total surface radiation. Especially at noon, the correlation coefficient can reach −0.62. In addition, in September and December, it was found that an increase of 1 $\mu g \cdot m^{-3}$ in $PM_{2.5}$ concentration would cause a decrease in total radiation of 1.8 W/m^2 and 0.5 W/m^2, a drop of ground surface temperature by 0.11 °C and 0.02 °C, and a drop of air temperature by 0.03 °C and 0.01 °C. Wu et al. [114] studied the impact of $PM_{2.5}$ on the urban heat island (UHI) and found that higher $PM_{2.5}$ concentrations leads to lower UHI intensity, especially during the daytime and the UHI can be reduced by up to 1 K.

The changes in the concentration of particulate matter can affect the formation processes of cloud and rainfall, and indirectly affect climate change. In the formation of rain, it is necessary to have a nucleus of condensation in order to form raindrops from water vapor. Other than salt in the seawater, the sources of nucleus of condensation come from $PM_{2.5}$. If there are too many particles, they may "eat away water", so that the raindrops in the sky are not growing, then, drizzle and clear weather days will become less than before. On the other hand, the existence of $PM_{2.5}$ might help to increase the number of condensation nuclei, so that possibility of rainfall will increase, and extreme rainstorm can even be produced. Therefore, in areas with heavy precipitation, $PM_{2.5}$ may encourage precipitation and bring more rainfall; while in areas with little precipitation, it may help to reduce rainfall. Simulation from Gui et al. [115] showed that the increase of aerosol particulates in different regions of China resulted in decreased air temperatures at the height under 2 m, decreased humidity ratio and precipitation in most parts of eastern China. Yao et al. [116] studied air pollution in the Jing-Jin-Ji region and its impact on evapotranspiration (ET). They suggested that $PM_{2.5}$ concentration has a significant negative effect on ET in most cities and that amount of water for agricultural irrigation could be reduced at high $PM_{2.5}$ concentrations. In addition, $PM_{2.5}$ can also aggravate or mitigate the acidification of rainwater in the pollution area, depending on the major components of the ions contained in $PM_{2.5}$. Li and Zhang [117] sampled and analyzed data on precipitation and $PM_{2.5}$ in Xi'an in 2011, and found that $PM_{2.5}$ in Xi'an is acidic, which is in consistent with the pH value of the precipitation.

3.3. Impact on Human Health

As early as in the 1980s, a large number of epidemiological studies abroad have shown that $PM_{2.5}$ has obvious side effects on human health [118–121]. The studies in China on the relationship between $PM_{2.5}$ and human health also fully proved that $PM_{2.5}$ can cause increases in the incidence of pulmonary heart disease [122], respiratory disease [123], cardiovascular disease [124], cancer [125,126] and other diseases, and even the death risk [127–129]. Long-term exposure to ambient $PM_{2.5}$ might be an important risk factor of hypertension and is responsible for significant hypertension burden in adults in China [130,131], and it leads to reduced lung function [132,133]. $PM_{2.5}$ is a risk factor for asthma [134,135], and it was related to the onset of children cough variant asthma by reducing immune regulation and ventilatory function [136]. $PM_{2.5}$ exposures might affect reproductive health. Significantly decreased fertility rates by 2.0% per 10 $\mu g \cdot m^{-3}$ increment of $PM_{2.5}$ were observed in [137]. Wu et al. [138] found that ambient PM exposure during sperm development adversely affects semen quality, in particular sperm concentration and count. However, Zhou et al. [139] argued that air PM_{10} and $PM_{10–2.5}$ (2.5 ≤ cut sizes ≤ 10 μm) exposures, not $PM_{2.5}$, are risk factors of semen quality. In addition, the indoor $PM_{2.5}$ exposure levels were positively associated with skin aging manifestation, including score of pigment spots on forehead and wrinkle on upper lip [140]. $PM_{2.5}$ may lead to induced DNA damage and cell cycle arrest in lung tumorigenesis [141]. Repeated exposure to $PM_{2.5}$

induces vascular inflammation [142]. Measles incidence was found to be associated with exposure to ambient $PM_{2.5}$ [143]. Significant associations between $PM_{2.5}$ and acute coronary syndrome (ACS) have also been found in most studies [144]. $PM_{2.5}$ may induce oxidative stress and inflammatory responses in human nasal epithelial cells, thereby leading to nasal inflammatory diseases [145]. Ambient $PM_{2.5}$ concentrations were significantly associated with influenza-like-illness risk [146].

PM$_{2.5}$ is associated with mortality. There are papers and reports on $PM_{2.5}$ sources and associated mortality in China as part of the Global Burden of Disease (GBD). It was estimated that the global premature mortality by $PM_{2.5}$ was at 3.15 million/year in 2010 with China being the leading country with about 1.33 million [147]. Lin et al. [148] found significant associations between $PM_{2.5}$ daily exceedance concentration hours (DECH) and cardiovascular mortality (3.0–5.02% increase in mortality rate per 500 $\mu g \cdot m^{-3}$ increase in $PM_{2.5}$). Health burden study by Song et al. [127] suggested that $PM_{2.5}$ in 2015 contributed as much as 40.3% to total stroke deaths, 33.1% to acute lower respiratory infection (ALRI, <5 years) deaths, 26.8% to ischemic heart disease (IHD) deaths, 23.9% to lung cancer (LC) deaths, 18.7% to chronic obstructive pulmonary disease (COPD) deaths, 30.2% to total deaths combining IHD, stroke, COPD, and LC, 15.5% to all cause deaths. Electronic hospitalization summary reports derived from 26 major cities in China between 1 January 2014 and 31 December 2015 showed that $PM_{2.5}$ had a negative impact on incidence of delirium, which is an independent risk factor for morbidity and mortality among older surgical adults [149]. The non-accidental mortality rate increases with exposure to extreme weather condition, especially hot dry synoptic weather types (SWT) and warm humid [150]. The effects of ambient air pollution and temperature triggered out-of-hospital coronary deaths (OHCDs) in China [151]. It was found that there is a spatial correlation between the mortality of respiratory diseases in Chinese provinces, corresponding to the spatial effect of $PM_{2.5}$ pollutions [152].

Some scholars have conducted studies on specific groups of people. For example, Li et al. [153] studied the relationship between pregnant women's exposure to $PM_{2.5}$ and the birth weight of newborns. Cheng et al. [154] pointed out that exposure of pregnant women in the third trimester, especially half a month before delivery, to high concentrations of $PM_{2.5}$, will lead to an increased risk of preterm birth. It might also be associated with low birth weight (LBW) and small for gestational age (SGA) [155]. Chen et al. [156] showed that the allergenicity in children is potentially related to the indoor $PM_{2.5}$ component and its content by comparing the toxicity of cells of allergic and non-allergic children exposed to indoor $PM_{2.5}$. Tu [157] pointed out there is an impact of $PM_{2.5}$ in Nanchang on the increase in outpatient pediatric respiratory disease outbreaks, with a maximum cumulative lag effect of 5 days. A 10 $\mu g \cdot m^{-3}$ increase of $PM_{2.5}$ concentration in the atmosphere resulted in 0.43% increase of respiratory disease outpatient visits. Ouyang et al. [158] found that the $PM_{2.5}$ concentrations are positively correlated with pneumonia hospitalization number of children, and their effect on boys is more obvious than that in the girls. $PM_{2.5}$ was independently associated with the risk of intensive care unit admission due to pneumonia (ICUp), and the maximum effect occurred at 3 to 4 days after exposure [159]. There were positive correlation between high concentrations of $PM_{2.5}$ and increasing daily emergency room visits [160]. In addition, $PM_{2.5}$ might also affect people's mental health. When exposed in haze weather for a long time, people could easily become depressed; in severe cases depression might also be induced. Study from Jia et al. [161] indicated that $PM_{2.5}$ exposure might negatively affect mood regulation and increase the risk of mental disorder.

3.4. Impact on Human Behavior

PM$_{2.5}$ is considered to be the "culprit" that causes hazy weather. It is harmful to people's health and at the same time has affected all aspects of people's living conditions. First of all, to cope with the frequent smog weather, people pay more and more attention to the prevention of $PM_{2.5}$ inhalation. Wearing an anti-haze mask has become a popular habit in China. Gu and Xie [162] pointed out that in haze weather residents would go out with anti-haze masks and would selectively adjust their outdoor activities or change their ways of transportation depending on the outside air conditions. Residents will change their window opening behavior, such as window opening time and size to prevent $PM_{2.5}$ penetration into the

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room [163,164]. Of course, turning on anti-haze air conditioners is also a preferred option due to their ability to reduce the $PM_{2.5}$ concentration while maintaining high level of indoor thermal comfort [165]. In addition, the hazy weather is disruptive to the effects of many scenic landscapes, and therefore many tourists will change their travel decisions during hazy weather [166].

4. Indoor and Outdoor $PM_{2.5}$ Relationship

4.1. Current Indoor $PM_{2.5}$ Pollution Status

According to a survey on the life style of the residents, people in China spent 85% of their time indoors, of which 50% of their time was spent inside the buildings. In particular, the elderly spent 90% of their time indoors, of which 76% of their time was in the residential buildings [167]. Therefore, an indoor environment with an acceptable indoor $PM_{2.5}$ mass concentration level is an essential prerequisite for healthy living of the residents. At present, there are not many researches on indoor $PM_{2.5}$ pollution in China. However, it can be concluded that existing $PM_{2.5}$ pollution in China is very serious (Table 3). Compared with the daily average limit of $PM_{2.5}$ level of 35 $\mu g \cdot m^{-3}$ based on China's latest ambient air quality standard, the $PM_{2.5}$ concentration level in almost all of the buildings in the cities studied in Table 3 exceed the limit. In some heavily polluted public spaces, the $PM_{2.5}$ concentration can exceed the limit by more than five times.

4.2. Ease of Indoor Environment Contaminated by Outdoor $PM_{2.5}$

Some researchers have suggested that outdoor $PM_{2.5}$ can enter the room through three ways, including natural ventilation, mechanical ventilation and infiltration [168]. For natural ventilation, the outdoor $PM_{2.5}$ was driven by wind pressure and thermal pressure into the interior of the building, and often there is no filter to remove the particle matters. For buildings with central air conditioning system, the fresh air was introduced by mechanical ventilation and go through air filters, however, the filters cannot removed all the particle matters and hence the $PM_{2.5}$ can enter the interior environment. The infiltration is related to air tightness. Due to the existence of cracks in the building envelope, the outdoor $PM_{2.5}$ will penetrate through the crack even when the doors and windows are fully closed. It is very important to evaluate how easily the indoor environment can be contaminated by outdoor $PM_{2.5}$. Currently, the indoor and outdoor particle concentration ratio (I/O ratio) and penetration coefficient are considered as two important parameters to be used for evaluation.

4.2.1. I/O Ratio

Most of the studies on I/O ratios were carried out based on field data measurement under natural ventilation or infiltration (see Table 4). From Table 4, it is found that the I/O ratios obtained by different researchers vary greatly. It could be due to the differences in the outdoor pollution level, outdoor weather conditions (outdoor wind speed, wind direction, temperature, humidity ratio, etc.), indoor sources of pollution, the conditions of the building envelope itself (the airtightness of the outer windows, the degree of sealing performance of the outer window with the wall, cracks over the wall, etc.), and the air changes per hour (ACH) [76,82,169–175]. Lin et al. [173] explored the difference of $PM_{2.5}$ pollution in Wuhan and Guangzhou. Strong seasonal variation patterns were found, and $PM_{2.5}$ pollution in Wuhan was more serious than that in Guangzhou. Through sampling data analysis, Zhou [174] found significant negative correlation among $PM_{2.5}$ mass concentration, temperature, and wind speed. Significant positive correlation between $PM_{2.5}$ mass concentration and relative humidity, and relatively weak relationship between $PM_{2.5}$ mass concentration and atmospheric pressure were found. Wang et al. [175] found the indoor $PM_{2.5}$ concentrations were affected by the outdoor $PM_{2.5}$ concentration and the degree of air tightness of the outer windows. Under the same outdoor $PM_{2.5}$ concentration, the outer windows with higher air-tightness were less prone to be affected by the outdoor $PM_{2.5}$.

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Table 3. Current status of indoor PM$_{2.5}$ pollution.

Building Type	Sampling Location	Sampling Condition	Average Indoor PM$_{2.5}$ Concentration ($\mu g \cdot m^{-3}$)	References	Times Exceeding Limit Set by Standard
Public place	Chongqing	Business hour	211 (68–468)	[176]	6.03
Public place	Ma'anshan	Business hour	133.73 (74.96–259.28)	[177]	3.82
Residential building	Lanzhou	Daily routine	Kitchen: 124.75 (48.14–279.25); Bedroom: 118.91 (38.34–367.62)	[178]	3.56; 3.40
Residential building	Nanjing	No cooking, no smoking	80 (47–113)	[179]	2.29
Hospital	Shenzhen	Business hour	36.71 (4.98–318.01)	[180]	1.05
Government agency	Tianjin	Business hour	71.0 (1–380)	[181]	2.03
Shopping mall	Beijing	Business hour	47 (9–253)	[182]	1.34
Market	Beijing	Business hour	56.21–61.36	[183]	1.61–2.25
Food court	Nanchang	Business hour	164 (38.03–492.73)	[184]	4.69

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Table 4. I/O (indoor/outdoor) ratio under different ventilation modes.

Ventilation Mode	Reference	Sampling Time Period	Building Type	Impact Factors of I/O Ratio	Results
Natural ventilation	[169]	1 December 2013–28 February 2014	Residential building	Outdoor $PM_{2.5}$ mass concentration level	When the outdoor $PM_{2.5}$ concentration is in the ranges of 0–33 $\mu g \cdot m^{-3}$, 34–65 $\mu g \cdot m^{-3}$, 66–129 $\mu g \cdot m^{-3}$, and $\geq$130 $\mu g \cdot m^{-3}$, the I/O ratios are 1.75, 1.05, 0.76 and 0.63, respectively
	[170]	April–December 2015 (one week per month, except in July and August)	School	Outdoor $PM_{2.5}$ mass concentration level, ACH, wind speed and outdoor air temperature	The time average I/O is 0.69. It varies in the range of 0.1–5.46. The I/O ratio decreases with the increases of outdoor $PM_{2.5}$ mass concentration level
	[171]	09:00–18:00, 13–15 March 2014	Laboratory complex building	ACH	48.7–57.3% of the $PM_{2.5}$ pollutants come from indoor sources and the I/O ratio varies 0.90–1.23
Infiltration	[172]	September 2013–August 2014	Office	Outdoor dry bulb temperature, relative humidity ratio and wind speed	The average ACH is 0.10 under mild weather, 0.22 when the wind speed is 1.6–3.4 m/s, 0.39 when the wind speed is 5.5–8.0 m/s. The corresponding I/O ratios are 0.43, 0.56 and 0.62, respectively
	[82]	Winter, 2014	Residential building	Indoor pollution sources	When the indoor $PM_{2.5}$ concentration reached its peak value, the I/O ratio was 0.67–0.89
	[76]	June 2013–August 2013; December 2013–February 2014	Office	Seasonal changes, wind speed and relative humidity ratio	The indoor and outdoor $PM_{2.5}$ concentrations in winter were higher than those in summer and the corresponding I/O ratios were also higher in winter than in summer

ACH: air changes per hour.

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4.2.2. Penetration Coefficient

Through surveys on people's window opening behavior, it is found that 60% of the people select to close the window under haze weather condition to prevent the outdoor $PM_{2.5}$ from entering the indoor environment [185]. In the case of closing the doors and windows, study on the penetration of $PM_{2.5}$ through the envelope cracks becomes particularly important. Some researches advised that the outdoor $PM_{2.5}$ entering the building envelope through the cracks is the process of "penetration" [168,185–187], where "penetration coefficient" is the decisive factor to evaluate the rate of $PM_{2.5}$ entering the indoor. Many foreign scholars obtained the penetration coefficients of fine particles through experimental measurements [187–189], e.g., Thatcher et al. [188] found that the penetration coefficient is larger for smaller fine particles. Some scholars in China have also conducted researches on determining the penetration coefficient. Their studies mainly focus on some influencing factors that affect the penetration coefficient of fine particles, such as the height of the crack [190], the roughness of the inner surface of the crack [191,192], the indoor/outdoor pressure difference [192], crack geometry [193], ACH [194] and so on. Due to the limitations of available devices and testing conditions, only a small number of studies in China currently focus on studying the penetration coefficient of $PM_{2.5}$ alone. Based on previous studies, Li [185] discussed on the outer window penetration coefficient of $PM_{2.5}$ is affected by multiple factors, including particle size, indoor/outdoor pressure difference, air exchange rate, and geometry and surface roughness of cracks in the building envelopes.

5. Indoor $PM_{2.5}$ Control

5.1. Air Filter and Air Conditioner Combination

Since the outdoor $PM_{2.5}$ pollution cannot be gotten rid of in the short run, it is important to control the indoor $PM_{2.5}$ pollution level to reduce its impact on occupants' health. Some researches focused on selection of certain combination of air filters. For example, Cao et al. [195] developed indoor $PM_{2.5}$ pollution control model under mechanical ventilation, and advised on how to select certain combination of air filters with different particulate removal efficiencies for a central AC system. Tu et al. [196] conducted test on filter efficiency based on particle sizing and counting method and $PM_{2.5}$ weight filtration method for multiple air filters of different materials and different particle removal efficiencies under the same experimental conditions. The relationship between these two filtration efficiencies provides a preliminary basis for the selection of $PM_{2.5}$ air filter for indoor air conditioning and ventilation system. Wang [197] studied the filtration performance of different grades of $PM_{2.5}$ filters and proposed suitable filter combination schemes based on the $PM_{2.5}$ pollution status in different regions. Comprehensive evaluations on the performance of different filter combination schemes were conducted, which could be used as references for the design of primary air conditioning system. Based on the principle of mass conservation, Lv [198] developed an indoor $PM_{2.5}$ concentration model of the primary return air-conditioning system and studied the impact of the changes of the filtration efficiency and the fresh air flow rate on the indoor $PM_{2.5}$ concentration, when the filters are installed in the primary air section, return air section and supply air section, respectively. The results from these researches can only be used for the primary air supply of the central air-conditioning system. It is worth mentioning that split air conditioner systems are installed in most of the residential buildings in China for indoor environment control. The split system is a ductless system. It has an outdoor unit and an indoor unit, where the inside (evaporative) heat exchanger is separated from the outside (condensing unit) heat exchanger. No fresh air systems are equipped. In general, the measures taken by the residents in China to deal with outdoor $PM_{2.5}$ pollution are to fully close the doors and windows. Hence, no fresh air can be treated by air filters and $PM_{2.5}$ can still penetrate through the cracks. It is far from enough to fight with $PM_{2.5}$ pollution by simply closing the doors and windows, so how to maintain a healthy indoor environment for buildings with split air conditioning system remains a problem to be solved in China.

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5.2. Development of New Material for Air Filters

Some researchers dedicated to the development of new filter materials. For example, Zhao et al. [199] reported that high efficiency and low resistance air purification materials made by electrospun polyvinylidene fluoride fiber (PVDF) doping with negative ion powders (NIPs) can have purification efficiency of up to 99.9%. Zhang et al. [200] utilized high-thermal-stability polyimide nanofibers to develop a highly effective polyimide nanofiber air filter. The efficiency of the filter to remove $PM_{2.5}$ from automobile exhaust at high temperatures can reach 99.5%. Li et al. [201] developed a reusable polyethersulfone hollow fiber membrane with high permeability using single-dry-jet wet-spinning technology. These filter materials have a high $PM_{2.5}$ capturing capacity, and if they can be widely used in air conditioning system, the burden to remove the indoor $PM_{2.5}$ will be greatly alleviated. However, due to the high initial investment cost, it is unrealistic to widely adopt this kind of filters in China.

Other researchers developed filters that can be attached to the window to allow air to flow through to reduce the filtering cost. For example, Liu et al. [202] introduced a polyacrylonitrile transparent filter that captures the PM through controlling the surface chemistry and microstructure of the air filters. It allows natural, passive ventilation to pass through the window and can achieve removal efficiency of up to 98.69% at transmittance of ~77% in haze weather. Zhao et al. [203] reported slip-effect functional nanofibrous membranes with purification efficiency of 99.09% and transmittance of 77% with low air resistance of 29.5 Pa. Khalid et al. [204] reported a blow-spinning technique for large scale coating of nanofiber transparent air filter on window screen which achieved standard $PM_{2.5}$ removal efficiency of >99% with 80% optical transparency. However, the study from Shi et al. [205] found that the mean value of harmonic average air exchange rate when the windows are open is far below the national standard. Therefore, more measures are needed to be taken to further reduce the filter resistance to enhance natural ventilation.

5.3. Anti-Haze Room Air Conditioners Available in the Market

Frequent episodes of hazy weather remind the residents of the importance and urgency to improve air quality, and it has become a driving force for the traditional air-conditioners to be upgraded with $PM_{2.5}$ purification functiond. Table 5 lists some of the popular AC products from different air conditioner companies with $PM_{2.5}$ purification function, which come from Midea, Haier, Panasonic, Gree and KELON. For example, the air conditioner (AC) products of Midea utilize a washable $PM_{2.5}$ purification module with an electronic generator to create an electric field in the dust collection device to captured charged particles, which effectively removes $PM_{2.5}$. The air conditioning products of Haier use visualization function to capture $PM_{2.5}$. Each AC unit is equipped with a 5-color indicator. When indoor $PM_{2.5}$ level exceeds the high limit, the indicator turns red and urge the occupants to turn on the $PM_{2.5}$ removal function, and it becomes blue when the indoor $PM_{2.5}$ level is back to normal. Panasonic air conditioners release negatively charged "nanoe-G" to be absorbed by $PM_{2.5}$ in the air, through which $PM_{2.5}$ is negatively charged and collected by electric field with high efficiency. The air conditioning products of Kelon use "three processes" (stripping technology, packaging technology and melting technology) for $PM_{2.5}$ purification. The air-conditioners listed are residential models, effective in room size of 10–50 m^2 (2650–7200 W).

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Table 5. Air conditioner with efficient PM$_{2.5}$ purification function.

Brand	Type	Capacity (W)	Energy Grade	Main PM$_{2.5}$ Removal Technology	PM$_{2.5}$ Removal Efficiency
Panasonic	KFR-36GW/BpSJ1S	3600	3	PM$_{2.5}$ air filter	84%
Haier	KFR-50LW/16UCP22AU1	5300	2	PET antibacterial and anti-mildew air filter	99%
Gree	KFR-26GW/(26571)FNBh-1	2650	1	Group filters with strong PM$_{2.5}$ capturing ability, primary air filter and high efficiency air filter	≥97%
KELON	KFR-72LW/EFVEA2(2N01)	7200	2	Inhibitory fins that inhibit the growth of 99.9% bacteria	≥99%
Midea	KFR-35GW/BP3DN1Y-QA100	3500	1	Washable PM$_{2.5}$ purifying module and dust collecting device	90%

6. Conclusions

The problem of PM$_{2.5}$ pollution in China is severe. It has seriously threatened the health of the residents. As compared with the developed countries, studies on PM$_{2.5}$ in China are still lagging behind. However, with the establishment of air quality standards for PM$_{2.5}$ in recent years and development of PM$_{2.5}$ monitoring stations nationwide in China, research on PM$_{2.5}$ in China has gradually been enhanced. The studies on PM$_{2.5}$ have increased exponentially, and more and more disciplines have got involved in the study on PM$_{2.5}$, which are mainly related to PM$_{2.5}$ source analysis, the impact of PM$_{2.5}$ on human health, relationship between indoor and outdoor PM$_{2.5}$ pollution levels and indoor PM$_{2.5}$ control. It is worth mentioning that there are several measurement methods and small differences in the measurement results of PM$_{2.5}$ concentration might be found. Most of the researches on I/O ratio and percentage of outdoor source contributions were based on the weighting method, which is a direct and reliable method. Generally speaking, the studies discussed throughout the paper will not be greatly affected with different measurement methods in various researches. There are still many shortcomings with current researches. For example, some studies only collected data in the typical month of the season or even a few days in a typical month. Although the data could be representative, they may also be incidental. Nowadays, depression, autism and other psychological diseases frequently occur, however, little research of PM$_{2.5}$ impact on mental health can be found in China. Most of the researches on the indoor and outdoor pollution correlations are conducted only for a specific building, i.e., under specific physical and meteorological condition [75–79], for example, in a residential apartment [75], or in an office building [76]. Although many useful results have been obtained from these studies, they depend largely on the experimental conditions at the time when data were collected and cannot be applied to more general situations. In addition, although the environmental monitoring network of PM$_{2.5}$ in the outdoor atmosphere is already established in China, the establishment of monitoring network on indoor air PM$_{2.5}$, which is more closely related to human health, is still lagging behind. It may be due to the facts that the indoor PM$_{2.5}$ pollution concentration limit is not clear in China. At the same time, the cost of creating household monitoring network is high, and it is difficult to carry out long time, standardized, PM$_{2.5}$ monitoring and data collection indoor.

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